

ENVIRONMENTAL ASPECTS OF PRODUCING ELECTRICITY FROM A COAL-FIRED POWER GENERATION SYSTEM - A LIFE CYCLE ASSESSMENT

Pamela L. Spath
Maraget K. Mann
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

A life cycle assessment (LCA) of different coal-fired boiler systems was performed at the National Renewable Energy Laboratory in collaboration with the Federal Energy Technology Center. Three designs were examined to evaluate the environmental aspects of current and future coal systems. The boundaries of the analysis include all material and energy streams from the following three subsystems: coal mining, transportation, and electricity generation. Upstream processes required for the operation of these three subsystems were included as well as any necessary waste disposal and recycling opportunities. Both surface and underground mining were examined with the coal being transported from the mine to the power plant via rail, a combination of rail and barge, or truck. Additionally, a sensitivity analysis was conducted to determine the parameters that had the largest effects on the conclusions. This paper discusses the results of the life cycle assessment including resource consumption, air and water emissions, wastes, and energy requirements.

INTRODUCTION

Life cycle assessment is a systematic method to identify, evaluate, and help minimize the environmental impacts of a specific process or competing processes. Material and energy balances are used to quantify the resource depletion, emissions, and energy consumption of all processes between transformation of raw materials into useful products and the final disposal of all products and by-products. Three cases were examined for this coal-to-electricity LCA: 1) a plant that represents the average emissions and efficiency of currently operating coal-fired power plants in the U.S. (this tells us about the status quo), 2) a new coal-fired power plant that meets the New Source Performance Standards (NSPS), and 3) a highly advanced coal-fired power plant utilizing a low emission boiler system (LEBS). The overall system consists of coal mining, transportation, and electricity generation. Upstream processes required for the operation of these three subsystems were also included in this study. All three coal systems are fueled with the same type of coal, Illinois No. 6, which will be excavated from mines located in central Illinois. The coal is either surface mined via strip mining or mined by the underground technique of longwall mining. The coal is transported via rail, a combination of rail and barge, or truck. Four different transportation cases were evaluated for this assessment: average user by land, average user by river, farthest user, and mine mouth. Other materials such as chemicals and wastes are transported via truck and rail. The information about the methodology and the results contained in this paper are taken from a larger, more detailed report (Spath and Mann, 1998).

AVERAGE PLANT

The average coal power plant consists of the following main equipment/process steps: pulverized coal boiler, baghouse filter, conventional limestone flue gas clean-up (FGC) system, heat recovery steam generator (HRSG), and steam turbine. The emissions for this case represent the average emissions from all U.S. coal-fired power plants in 1995. These were calculated by dividing the total coal-generated U.S. emissions of a particular pollutant on a weight basis (kg) by the total electricity generated (kWh) from coal in the U.S. To maintain a mass balance around the power plant, a specific plant with emissions similar to the calculated averages and which is feeding the designated type of coal for this LCA was identified. The actual resource requirements, final emissions, and energy consumption from this specific plant were used to represent the average power plant in this study.

NSPS PLANT

Emissions for this case are calculated based on flue gas clean-up removal efficiencies such that the power plant meets the New Source Performance Standards (NSPS). The following are the standards of performance in g/GJ heat input on a higher heating value basis, with lb/MMBtu in parenthesis, for new electric utility steam generating units using bituminous coal: NO_x = 260 (0.60), SO_x = 258 (0.60), and particulates = 13 (0.03). These values were taken from the Code of Federal Regulations, 40 CFR 60.42a, 60.43a, and 60.44a; new plants built after 1978 are required to meet these standards. Except for higher pollutant removal efficiencies achieved through boiler modifications and more advanced clean-up technologies, the process configuration for this case is the same as that for the average plant.

LEBS PLANT

Emissions for this case are those forecasted from a future plant utilizing a Low Emission Boiler System (LEBS). LEBS is projected to have significantly higher thermal efficiency, better performance, and a lower cost of electricity than current coal-fired power plants. The technology being considered in this assessment is by the developer DB Riley Inc., and is being researched under the Department of Energy's sponsorship. The objective of the LEBS program is to produce technologies that result in lower emissions such that the NO_x and SO_x emissions are 1/6 of the NSPS and the particulate emissions are 1/3 of the NSPS. The DB Riley technology uses a low-NO_x system with advanced burners, air staging, and a wet ash slagging system. The copper oxide flue gas clean-up process utilizes a regenerable sorbent, removing both SO₂ and NO_x from the flue gas and producing sulfuric acid or sulfur as a by-product instead of producing a solid waste. The sorbent is regenerated using natural gas as the reducing agent.

COAL MINING

For this study, both strip mining and underground longwall mining were examined. The resources, emissions, and energy use associated with the excavation of the coal were included in this LCA. The processes studied include raw material extraction, equipment manufacture, coal mining, coal preparation/cleaning, all necessary transportation of chemicals, etc., and all necessary upstream processes. The resources, energy, and emissions associated with the mining equipment are based on the types of machinery used for each coal excavation process, the fuel requirements, and the lifetime of the machinery. Additionally, the process steps involved in land reclamation are included in the surface mining option. Overall, the environmental impacts from surface versus underground mining are not significantly different in any of the three power plant cases examined (average, NSPS, and LEBS). The main difference between these two mining techniques is that the surface mining subsystem results in a higher amount of airborne ammonia emissions due to the production of ammonium nitrate explosives which are used at the mine. Another important difference is that underground mining requires limestone which emits a large amount of particulates during its production. Therefore, results in this paper are presented for the surface mining cases only.

COAL TRANSPORTATION CASES

The inventory assessment for the transportation subsystem includes the energy required and emissions generated for the transportation of coal by barge, train, or truck between the boundaries of the coal mining and power generation subsystems. The resources, energy, and emissions related to extracting crude oil, distilling it, producing a usable transportation fuel, and distributing it to refueling stations plus the emissions produced during combustion of the fuel were included in the total inventory. The material requirements for each of the various modes of transportation were used in determining the resources, energy, and emissions associated with vehicle production and decommissioning.

The following four transportation cases were examined for this study: (1) average user by land: railcar = 483 km, (2) average user by river: railcar = 48 km plus barge = 435 km, (3) farthest user: railcar = 1,538 km plus barge = 504 km, and (4) mine mouth: minimal truck transport = 2 km. The average user by land was determined based on the fact that most of the utilities serviced from the Perry County region fall within the distance of 483 km, which is the rail distance from E. St. Louis to Chicago. This distance also includes at least parts of the states of Illinois, Wisconsin, Iowa, Indiana, Kentucky, Alabama, Mississippi, and Missouri. When considering barge transport, the coal must first be hauled 48 km by rail to the Mississippi River before being loaded onto a coal barge. The barge distance of 435 km listed above for the average user by river case reaches up the Mississippi River to Iowa or down the river to the state of Mississippi and could include traffic up the Ohio River. The farthest user consists of rail transport to the Mississippi River (48 km) then river transport to Memphis, Tennessee (504 km) and finally rail transport to central Florida (1,490 km). The transferring of coal between rail and barge was not included but should be minimal compared to the actual transportation of the coal.

RESULTS: RESOURCE REQUIREMENTS

Fossil fuels, metals, and minerals are used in all of the processes steps required to convert coal to electricity. In terms of resource depletion, coal is used at the highest rate. For the average and NSPS cases, limestone and oil account for the majority of the remaining resources consumed compared to the LEBS case, where the bulk of the remaining resource consumption is natural gas and oil. Table 1 shows the majority of the resources used for each coal case studied.

Table 1: Resource Consumption

Resource	Average		NSPS		LEBS	
	% by	g/kWh	% by	g/kWh	% by	g/kWh
Coal	80.4	474.44	78.0	433.84	97.3	352.49
Limestone	17.4	102.84	19.7	109.49	0.0	0.04
Oil	1.9	11.48	2.0	11.32	1.3	4.88
Natural gas	0.2	1.25	0.2	1.26	1.3	4.53

- (a) Numbers are reported for the surface mining case. However, the underground mining numbers are similar to those listed above.
- (b) Transportation = average user by river.
- (c) Percent of total resource consumption. Not all resources consumed by the system are shown; therefore the numbers do not add up to 100%.
- (d) Resource consumption per kWh of net electricity produced averaged over the life of the system.

RESULTS: AIR EMISSIONS

In terms of total air emissions, CO₂ is emitted in the greatest quantity accounting for 98-99 wt% of the total air emissions for all cases examined. The following are the total CO₂ emissions for the average, NSPS, and LEBS case: 1,022 g/kWh, 941 g/kWh, and 741 g/kWh of net electricity produced. The majority of the CO₂, greater than 95%, is emitted from the power plant subsystem during operation of the coal-fired plant. As shown in Table 2, the next highest air emissions include particulates, SO_x, NO_x, CH₄, CO, and NMHCs. In all three coal cases the power plant produces most of the SO_x, NO_x, and CO while the methane comes primarily from the coal mine. For the average and NSPS case, the majority of the particulates come from the production of limestone. For the LEBS case, the majority of the particulates are emitted by the power plant during normal operation and the second major source of particulates is copper oxide production. For all three cases, the NMHC emissions are evenly distributed among the mining, transportation, and power plant subsystems. However, for the LEBS case it should be noted that a significant amount of the total NMHC emissions are emitted during natural gas production.

Table 2: Air Emissions (Excluding CO₂)

Air	Average		NSPS		LEBS	
	% by	g/kWh	% by	g/kWh	% by	g/kWh
Particulates	44.3	9.21	61.0	9.78	4.4	0.11
SO _x	32.2	6.70	15.7	2.53	28.0	0.72
NO _x	16.1	3.35	14.6	2.34	21.3	0.54
CH ₄	4.4	0.91	5.2	0.84	27.9	0.75
CO	1.3	0.27	1.5	0.25	7.5	0.19
NMHCs (e)	1.0	0.21	1.3	0.20	7.5	0.19

- (a) Numbers are reported for the surface mining case. However, the underground mining numbers are similar to those listed above.
- (b) Transportation = average user by river.
- (c) Percent of total air emissions *excluding* CO₂ emissions. Not all resources consumed by the system are shown; therefore the numbers do not add up to 100%.
- (d) Air emissions per kWh of net electricity produced averaged over the life of the system.
- (e) NMHCs = non-methane hydrocarbons including volatile organic compounds (VOCs).

RESULTS: WATER EMISSIONS AND WASTES

For all three coal cases, the majority of the water emissions from the system occurred in the mining and power plant subsystems. The water emissions were evenly distributed between these two subsystems. In general, though, the total amount of water pollutants was found to be small compared to other emissions.

A large amount of the solid waste in the average and NSPS cases comes from the power plant in the form of flue gas clean-up waste and ash that must be landfilled, 58-61% and 20-23% of the total waste, respectively. For these two cases, non-hazardous solid waste accounts for the balance of the total waste and the majority of this waste is generated during limestone production. The flue gas clean-up process for the LEBS case utilizes a regenerable sorbent, therefore, the bulk of the waste

from this system is ash which accounts for 87-93% of the total waste. The remaining waste for the LEBS case is non-hazardous solid waste which primarily comes from the mining operations.

RESULTS: ENERGY

The energy use within the system was tracked so that the net energy production could be assessed. Several types of efficiencies can be defined to study the energy budget of the coal system. The first being the power plant efficiency defined in the traditional sense as the energy delivered to the grid divided by the energy in the feedstock to the power plant (coal and natural gas in the LEBS case). Four other types of efficiencies can be defined as follows:

Table 3: Energy Efficiency and Ratio Definitions

Life cycle efficiency (%) (a)	External energy efficiency (%) (b)	Net energy ratio (c)	External energy ratio (d)
$\frac{Eg - Eu - Ec - En}{Ec + En}$	$\frac{Eg - Eu}{Ec + En}$	$\frac{Eg}{Eff}$	$\frac{Eg}{Eff - Ec - En}$
where: Eg = electric energy delivered to the utility grid Eu = energy consumed by all upstream processes required to operate power plant Ec = energy contained in the coal fed to the power plant En = energy contained in the natural gas fed to the power plant (LEBS case only) Eff = fossil fuel energy consumed within the system (e)			

- (a) Includes the energy consumed by all of the processes.
- (b) Excludes the heating value of the coal and natural gas feedstock from the life cycle efficiency formula.
- (c) Illustrates how much energy is produced for each unit of fossil fuel energy consumed.
- (d) Excludes the energy of the coal and natural gas to the power plant.
- (e) Includes the coal and natural gas fed to the power plant since these resources are consumed within the boundaries of the system.

The net energy ratio is a more significant measure of the net energy yield from the system than the external energy ratio because it accounts for all of the fossil energy inputs. The following table contains the resulting efficiencies and energy ratios for each coal case.

Table 4: Efficiencies and Energy Ratio Results

Case (1*, 2*)	Power plant efficiency (%) (3*)	Life cycle efficiency (%) (3*)	External energy efficiency (%) (3*)	Net energy ratio	External energy ratio
Average	32	-76	24	0.29	5.0
NSPS	35	-73	27	0.31	5.1
LEBS	42	-66	34	0.38	6.7

- (a) Coal LCA numbers are reported for the surface mining case. However, the underground mining numbers are similar to those listed above.
- (b) Transportation = average user by river
- (c) Efficiencies are on a higher heating value basis.

One of the most surprising results of this study was that upstream processes consumed such great quantities of energy. Intuitively obvious is the fact that because the power plant efficiency is less than one, the net energy ratio, which includes the energy in the coal consumed by the power plant, will be a fractional value. However, in subtracting out the energy of the coal feed in the external energy ratio, one would expect the results to be much higher than they are. However, in the average and NSPS cases, limestone production was found to require a significant amount of energy; in the LEBS case, excluding the coal feed, the majority of the total energy is used in natural gas production. Limestone production accounts for 25% and 28% of the total system energy consumption for the average and NSPS cases, respectively, and for the LEBS case natural gas production accounts for 37% of the total system energy consumption.

For all three cases examined (average, NSPS, and LEBS), a large amount of energy was also consumed by the transportation subsystem (except for the mine mouth case), primarily from the energy required to extract crude oil, distill it, produce a usable transportation fuel, and distribute it to refueling stations. The following percentages are for surface mining and transportation via the average user by river case. For all three power plant cases the energy consumption for the fuel required to transport the coal by a combination of train and barge accounts for 30-33% of the total system energy consumption.

SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to determine the parameters that had the largest effects on the results and to determine the impact of estimated data as well as variations in data on the conclusions. The following variables had the largest effect on resource consumption, emissions, and energy usage: reducing the power plant construction materials, changing the power plant operating capacity factor, and increasing or decreasing the transportation distance. Varying the amount of mining methane emissions had a large impact on the overall methane emissions from the system, however, this variable will be site-specific and ultimately should be examined on a case by case basis. Changing the power plant efficiency or changing the coal transport distance are the only variables that had a noticeable effect on the efficiency and energy ratio results. In all sensitivity cases tested, however, the net energy ratio varied by only small amounts, mostly due to the energy in the coal feed, the energy consumed in limestone and natural gas production, and the energy used in transportation. For the average, NSPS, and LEBS cases, the net energy ratios range from 0.24 - 0.33, 0.27 - 0.36, and 0.33 - 0.42, respectively.

CONCLUSIONS

Overall, the environmental impacts from surface versus underground mining are not significantly different in any of the three power plant cases examined (average, NSPS, and LEBS). As expected, the majority of the overall methane emissions come from the mine itself. However, as stated above these emissions are site-specific and ultimately should be evaluated on a case by case basis. Additionally, about half of the system's water emissions come from the mining subsystem.

For the average and NSPS cases a large amount of the total energy requirement for the power generation subsystem comes from limestone production whereas for the LEBS case the majority of the total energy is required for natural gas production. Therefore, even with increased power plant efficiency, the overall system energy balance of coal-fired power plants will not increase significantly unless technologies can be developed to reduce upstream energy consumption.

Of the three subsystems examined (coal mining, transportation, and electricity generation), transportation required the least amount of resources and had the lowest air, water, and solid waste emissions even when considering the farthest user case. However, the energy consumption for this subsystem was significant (excluding the mine mouth case). As anticipated, for mine mouth operation, all resource consumption, emissions, and energy usage are a small percentage of the total over the life of the system. For the other three transportation cases (average user by river, average user by land, and farthest user) oil consumption as well as a few air and water emissions are high. It was found that the transportation distance has a significant effect on the oil consumption, a few of the system's emissions, and the energy consumption whereas the mode of transportation has virtually no effect on the results.

In all three coal cases the power plant produces the majority of the SO_2 , NO_x , and CO . Also, half of the water emissions occurred in the power plant subsystem. Most of the solid waste in the average and NSPS cases comes from the power plant in the form of flue gas clean-up waste that must be landfilled. For these two cases there is also a high percentage of ash which is landfilled and limestone production produces a considerable amount of non-hazardous solid waste. The flue gas clean-up process for the LEBS case utilizes a regenerable sorbent, therefore, the primary waste from this system is ash. As expected, the LEBS plant requires fewer resources and energy and produces fewer emissions and waste per unit of energy delivered to the utility grid than the average or NSPS cases. The life cycle efficiency, external energy efficiency, net energy ratio, and external energy ratio are similar for the average and NSPS plant. The energy efficiency and ratio numbers are all somewhat higher for the LEBS.

FUTURE WORK

The primary goal of this life cycle assessment was to assess the environmental aspects of producing electricity from a coal-fired power system. The focus of this initial work was on an inventory of all resources, environmental emissions, and energy flows of the system, studied in a cradle-to-grave manner. Therefore, a comparative analysis was not performed at this time. Ultimately, the resulting emissions, resource consumption, and energy requirements of this system will be compared to a previously completed LCA of electricity production from a biomass gasification combined-cycle (BIGCC) power plant (Mann and Spath, 1997) and a study currently being conducted which involves co-firing biomass in a coal-fired boiler.

REFERENCES

1. P.L. Spath and M.K. Mann. (1998) "Life Cycle Assessment of Coal-fired Power Production," National Renewable Energy Laboratory, Golden, CO. TP-570-25119.
2. Office of the Federal Register National Archives and Records Administration. (1996) *Code of Federal Regulations. Protection of Environment*. Title 40. Part 60, July.
3. M.K. Mann and P.L. Spath. (1997) "Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System," National Renewable Energy Laboratory, Golden, CO. TP-430-23076.